Development of a Compact Fusion Device based on the Flow Z-Pinch
The Fusion Z-Pinch Experiment: FuZE

2015 ARPA-e Kickoff Meeting
Santa Fe, NM

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Harry S. McLean

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UNIVERSITY of WASHINGTON

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Lawrence Livermore National Security, LLC

Outline

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Existing Device (ZAP) Results: Axial plasma flow with velocity shear in the radial direction has been shown to stabilize a 1 m long x 1 cm diameter 50 kA z-pinch column for 20-40 usec

Volume 75, Number 18 PHYSICAL REVIEW LETTERS 30 October 1995

Sheared Flow Stabilization of the $m = 1$ Kink Mode in Z Pinches

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Volume 87, Number 20 PHYSICAL REVIEW LETTERS 12 November 2001

Evidence of Stabilization in the Z-Pinch

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D. J. Den Hartog*

PHYSICS OF PLASMAS VOLUME 10, NUMBER 5 MAY 2003

Sheared flow stabilization experiments in the ZaP flow Z pinch[a]

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(Received 7 November 2002; accepted 9 January 2003)

IOP Publishing and International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion **49** (2009) 075039 (9pp) doi:10.1088/0029-5515/49/7/075039

Equilibrium, flow shear and stability measurements in the Z-pinch

U. Shumlak, C.S. Adams, J.M. Blakely, B.-J. Chan, R.P. Golingo, S.D. Knecht, B.A. Nelson, R.J. Oberto, M.R. Sybouts and G.V. Vogman
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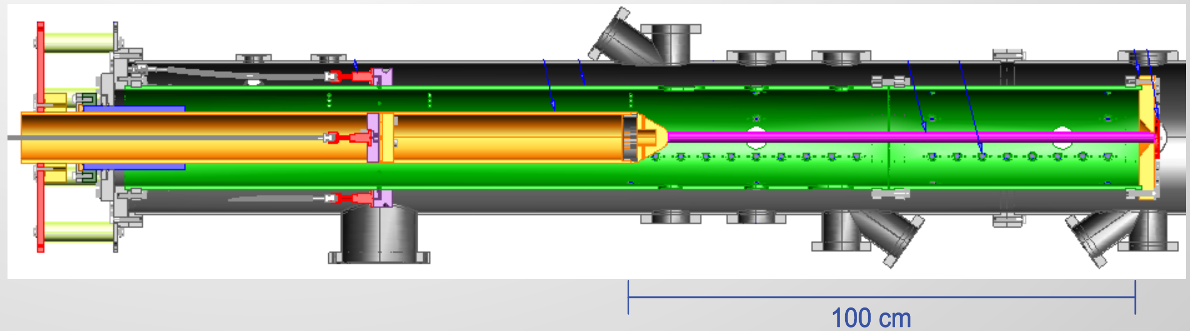
Abstract
The stabilizing effect of a sheared axial flow is investigated in the ZaP flow Z-pinch experiment at the University of Washington. Long-lived, hydrogen Z-pinch plasmas are generated that are 1 m long with an approximately 10 mm radius and exhibit gross stability for many Alfvén transit times. Large magnetic fluctuations occur during pinch assembly, after which the amplitude and frequency of the fluctuations diminish. This stable behaviour continues for an extended quiescent period. At the end of the quiescent period, fluctuation levels increase in magnitude and frequency. Axial flow profiles are determined by measuring the Doppler shift of plasma impurity lines using a 20-chord spectrometer. Experimental measurements show a sheared flow that is coincident with low magnetic fluctuations during the quiescent period. The experimental flow shear exceeds the theoretical threshold during the quiescent period, and the flow shear is lower than the theoretical threshold at other times. The observed plasma behaviour and correlation between the sheared flow and stability persists as the amount of injected neutral gas and experimental geometry are varied. Computer simulations using experimentally observed plasma profiles show a consistent sheared flow stabilization effect. Plasma pinch parameters are measured independently to demonstrate an equilibrium consistent with radial force balance.

PACS numbers: 52.30.−q, 52.35.Py, 52.55.Dy, 52.58.Lq

(Some figures in this article are in colour only in the electronic version)



Nucl. Fusion **49** (2009) 075039 U. Shumlak *et al*

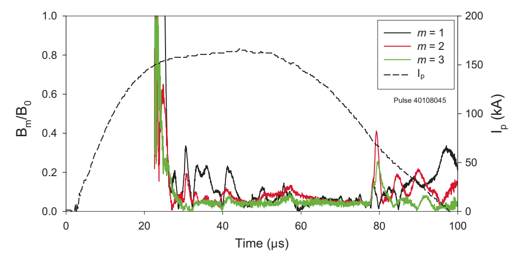


Figure 2. Time evolution of Fourier components of the normalized magnetic field fluctuation at $z = 0$ for the $m = 1, 2, 3$ modes for the original 0.1 m diameter inner electrode. The values are normalized to the average magnetic field value. A quiescent period is evident from 42 to 79 μs which defines the normalized time $\tau = 0$ to 1 for this pulse. The evolution of the total plasma current (dashed curve) is included for reference.

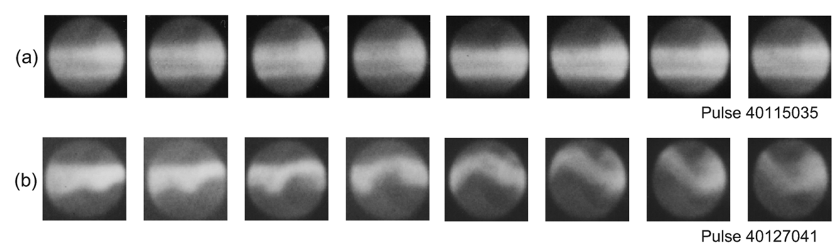


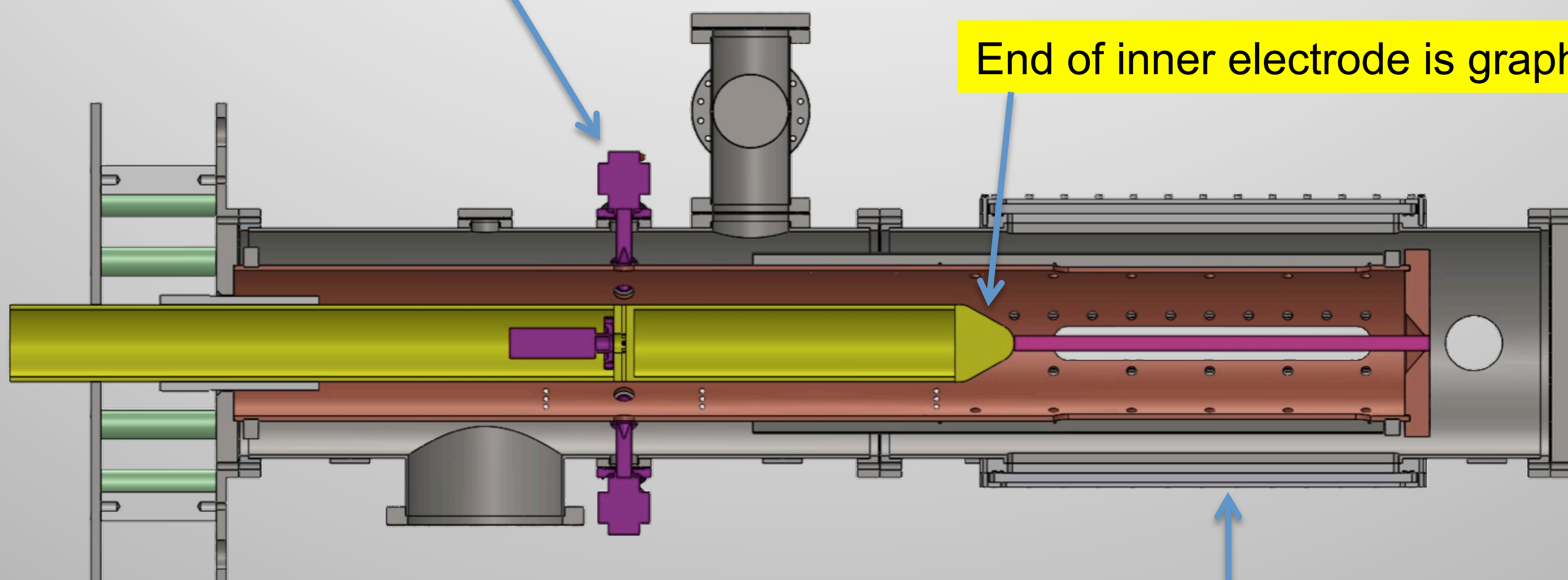
Figure 3. Fast framing camera images of visible light from the plasma viewed through a 5 cm hole at $z = 0$. Images are taken every 200 ns during a single plasma pulse. (a) Images obtained during 47.7–49.1 μs, the middle of the quiescent period. (b) Images obtained during 75.3–76.7 μs, near the end of the quiescent period.

Stable for:
$T_{quiescent}$ ~ 40 uS
I_{pinch} ~ 50 kA

The new device under construction (FUZE) is about the same dimensions but will handle much higher discharge current, higher heat loads, and will provide flexible gas injection capability with a total of 9 fast-puff gas valves.

Gas valves are now external at 8 locations plus one inside the inner electrode on axis
Nozzles extend through vacuum envelope to the outer electrode

End of inner electrode is graphite

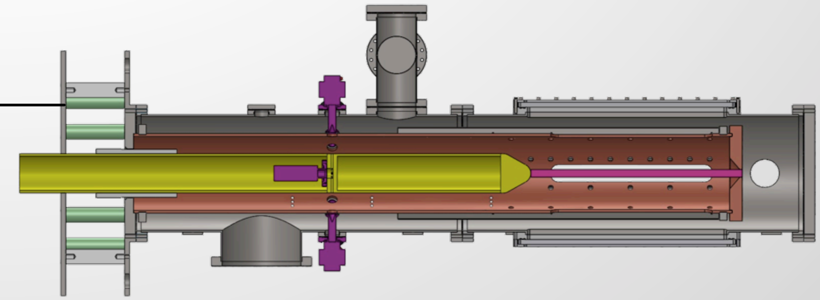


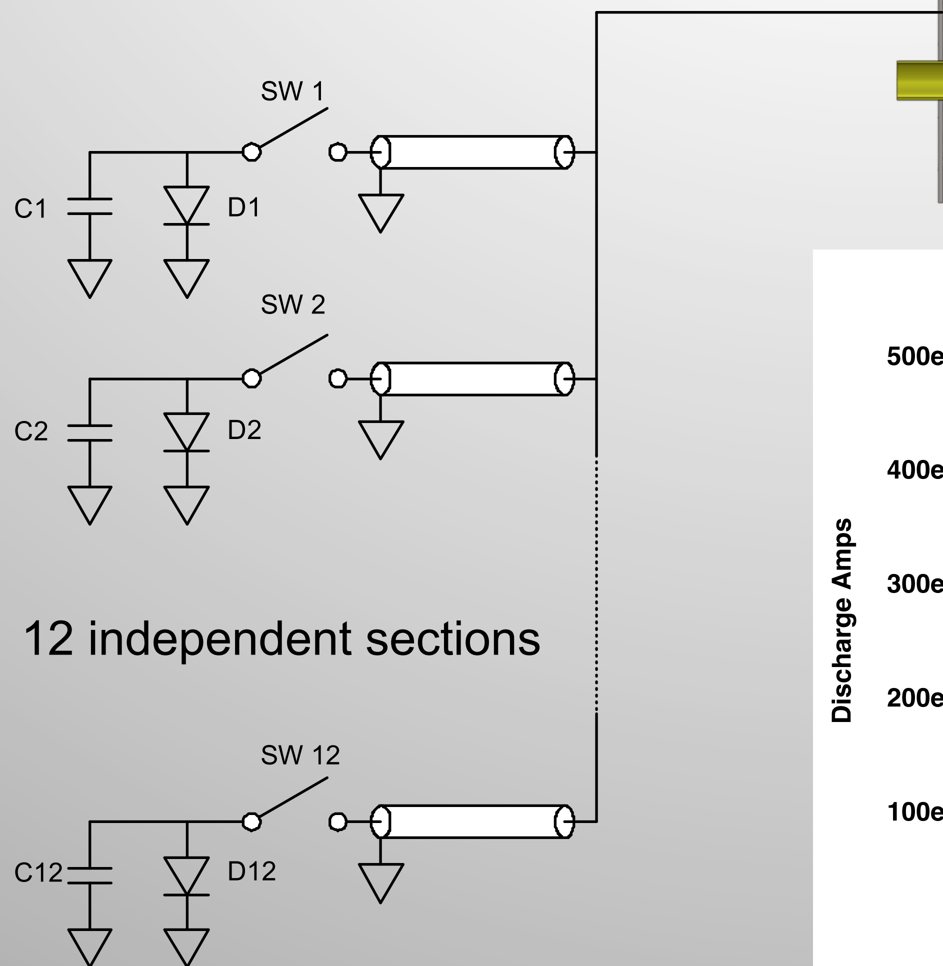
Plasma gun region gun is very similar

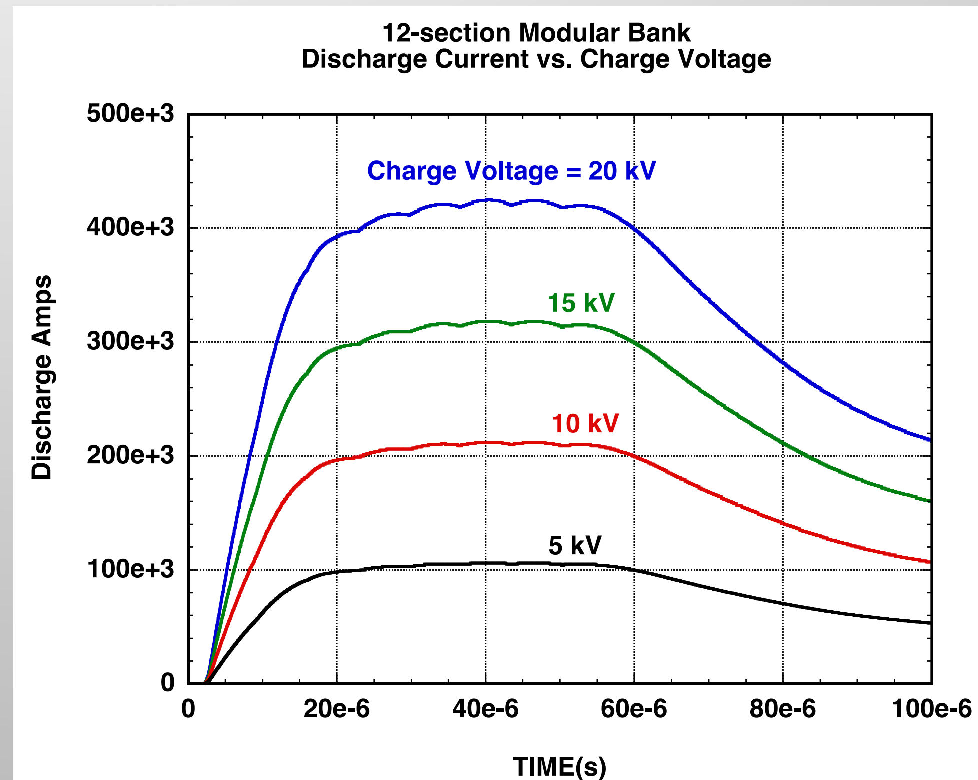
Larger vacuum pumping ports at multiple locations

Pinch region is shorter, but can be easily changed

We will drive the new electrode set with a capacitor bank that has 12 independently triggerable sections-This provides excellent flexibility in current pulse shape.



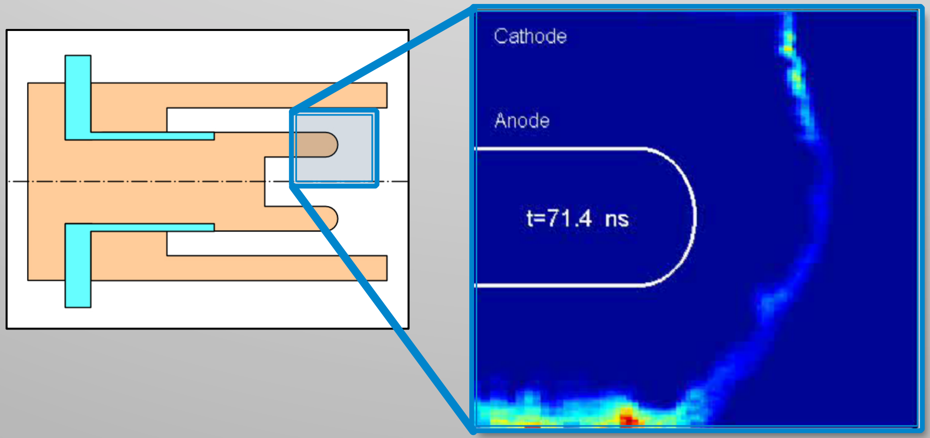




To help understand the physics in detail, we will apply state of the art fluid and kinetic particle plasma simulation codes.

- The physics inside the pinch is complicated and a kinetic, or particle, approach is needed to properly simulate pinch conditions. Fluid approaches do not capture kinetic instabilities or kinetically-driven anomalous plasma viscosity/resistivity.

- Schmidt et al have modeled a similar device, the dense plasma focus (DPF) in the particle-in-cell code LSP [2] and demonstrated that a fully kinetic approach was needed to reproduce experimentally measured neutron yields, ion beam energies, and electromagnetic oscillations. In this project, we will extend the kinetic modeling to a flow pinch geometry.



Fully kinetic pinch model
A. Schmidt, V. Tang, D. Welch, PRL 2012

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To understand how the system scales with current we apply an equilibrium power balance ($P_{in} = P_{out}$) in the plasma:

- P_{in}
  - P_{ohmic}
  - $P_{compression}$
  - P_{flow}
  - $P_{alpha\_heating}$

=

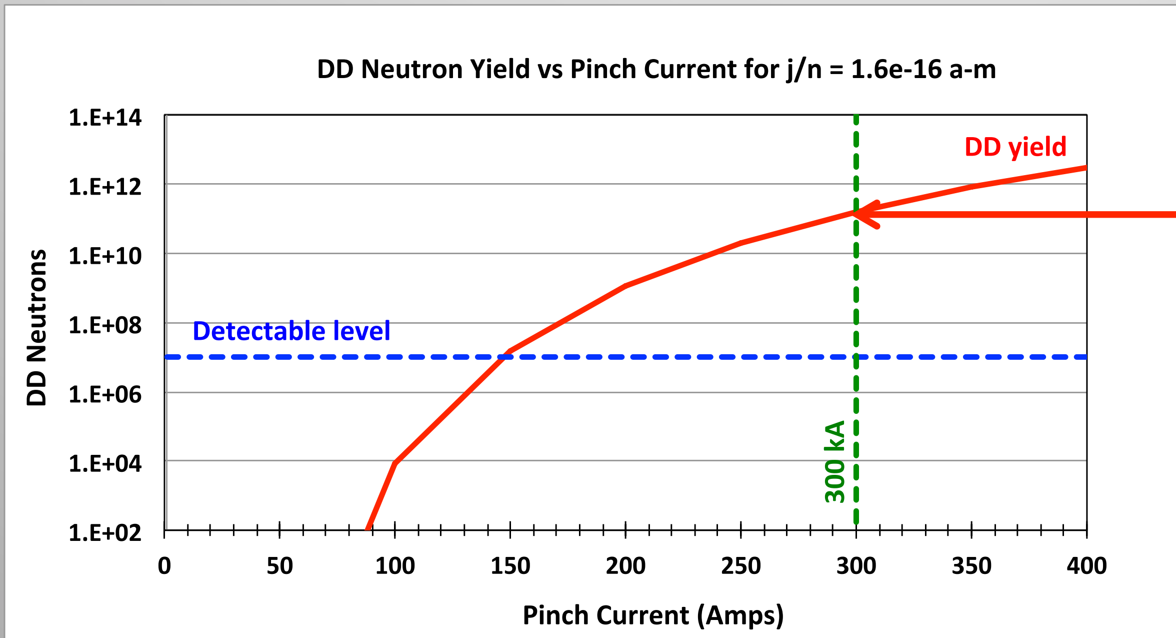
- P_{out}
  - $P_{radiation}$
  - $P_{conduction}$
  - P_{flow}
  - $P_{thermal}$

- Assumptions:
  - Bennett pinch equilibrium $nk\left(T_e + ZT_i\right) = \dfrac{B^2}{2\mu_0}$; $B = \dfrac{\mu_0 I}{2\pi a}$; a = pinch radius
  - Flat current, density, temperature profiles across pinch
  - $V_{flow} = 0.1\ V_{alfvén}$
  - P_{rad} is bremsstrahlung only, $Z_{eff} = 2.0$
  - $P_{conduction}$ is ad-hoc, using D_{bohm} * multiplier to match experimentally-measured pinch radius at 50 kA. Conduction losses are not understood and usually ignored.
  - Spitzer Resistivity, look over a range in 0.8 e -14 amp-m < j/n < 1.6 e -14 amp-m
    - How j/n adjusts is also not well-understood. Density and current profiles adjust when $u_{e,drift}$ = j/en approaches ion sound speed → pinch needs to heat during current ramp or bad things will happen
  - $P_{thermal} = U_{thermal} / t_{flow}$ where $t_{flow} = Length_{pinch} / V_{flow}$
    - The entire thermal energy of the pinch is dumped on the end wall every flow time and is, by far, the largest power loss in the system at reactor conditions (exceeding ohmic and conduction losses during ramp-up)

Power scaling projections show that reaching 300 KA with deuterium produces useful intensities of neutrons and x-rays, suitable for a variety of applications

Plasma Conditions	Existing (ZAP)	ALPHA (FUZE)	Reactor
Pinch current (kA)	50	300	1500
Total discharge (kA)	150	500	1700
Pinch radius (mm)	10	0.7	0.05
Ion Density (m^{-3})	1 E+22	2.5 E+24	3 E+27
Temperature	50-100 eV	2500-4000 eV	25-50 keV
Magnetic field (tesla)	1	90	6000
Lawson n-tau (m^{-3} sec)	1E+17	1E+19	1E+21
D-D Neutron Yield		1e11 - 4e11	
Radiation Power (MW)		10 MW	

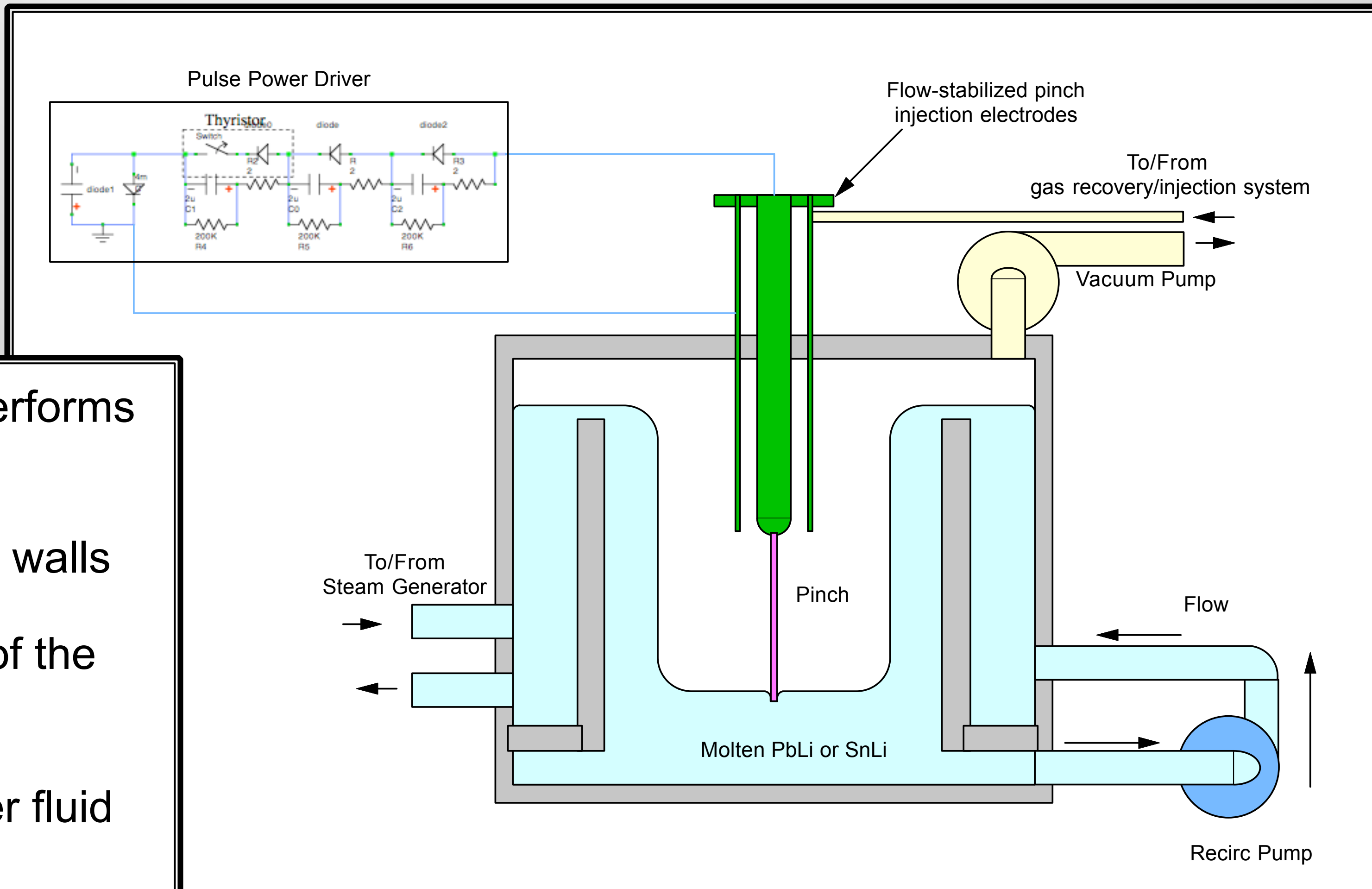
Xray Source at 300 kA:
- Hot: 2keV
- Intense: 10 MW
- Long pulse > 10 usec
- Energetic: 100 J/pulse



Neutron Source at 300 kA:
- 2.45 MeV neutrons
- 4e11 yield per pulse
- 0.160 J / pulse

Shear-Flow Stabilized Z-Pinch Reactor Concept:

- Point a flow-stabilized z-pinch down into liquid metal
- Addresses many technology issues that are unresolved for other concepts



Liquid metal performs multiple jobs:

- Protects the walls
- Act as one of the electrodes
- Heat transfer fluid

Ignitron technology is a mature technology with commercially available units that can conduct reactor-scale relevant currents through liquid cathodes

NATIONAL

NL-9000
Ignitron

The NL-9000 is a size "E" dual bath cooled ignitron intended for use as a high energy switch in capacitor circuits. The following ratings are at this printing maximum and may be exceeded only with the end users full liability.

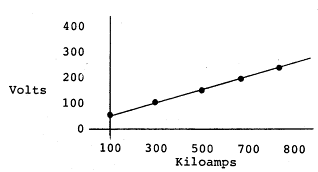
Anode Material- **NL9000** - "Graphite" **NL9000A** - "Stainless"

GENERAL:[1]
Mercury pool electronic tube, water cooled
Number of electrodes:
Main anode ---------- 1
Ignitors ---------- 2
Cathode "Body with Hg Pool" ---------- 1

IGNITORS:
Forward Voltage "open circuit" ---------- 1000-3500 V
Inverse voltage ---------- 5 V
Current peak "short circuit" ---------- 200-500 A
Length of firing pulse ---------- 5-15 usec
Net weight, approximately ---------- 60 lbs

COOLING REQUIREMENTS:
Flow minimum at peak current ---------- 6 GPM
Temperature range[2]
Cathode cup ---------- 15-25° C
Side Walls ---------- 15-45° C

MAXIMUM RATING: DAMPED DISCHARGE (NON-SIMULTANEOUS RATING)
Peak forward or inverse voltage ---------- 10 kV[5]
Peak anode current[3] ---------- 700 kA
Coulombs per pulse at max amps ---------- 250 C
Pulse repetition rate per minute ---------- 1



TUBE DROP AT PEAK CURRENT
DAMPED SINUSOID I peak 150us

NATIONAL ELECTRONICS
A Division of Richardson Electronics, Ltd.
LaFox, IL 60147 (630) 208-2300

700 kA rating

- Flow-stabilized pinch requires ~ 1-1.5 MA to reach reactor conditions.

Figure 19. Size E (9-in.) NL9000 close-spaced, hollow-anode tube.

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References

1. C.W. Hartman, G. Carlson, M. Hoffman, R. Werner, and D.Y. Cheng. A conceptual fusion reactor based on the high-plasma-density z-pinch. Nuclear Fusion, 17(5):909, 1977
2. C. W. Hartman, J. L. Eddleman, R. Moir, and U. Shumlak. The Flow-Through Z-Pinch For Fusion Energy-Production. Fusion Technology, 26(3, Part 2):1203–1206, Nov 1994
3. U. Shumlak and C. W. Hartman. Sheared flow stabilization of the m=1 kink mode in Z pinches. Physical Review Letters, 75(18):3285–3288, Oct 1995.
4. U. Shumlak and N. F. Roderick. Mitigation of the rayleigh–taylor instability by sheared axial flows. Physics of Plasmas, 5(6):2384–2389, 1998
5. U. Shumlak, R. P. Golingo, B. A. Nelson, and D. J. Den Hartog. Evidence of stabilization in the Z-pinch. Physical Review Letters, 87(20):205005, Oct 2001
6. R. W. Moir, R. H. Bulmer, T. K. Fowler, T. D. Rognlien, and M. Z. Youssef. Spheromak magnetic fusion energy power plant with thick liquid-walls. Fusion Science and Technology, 44(2):317–326, September 2003
7. U. Shumlak, B. A. Nelson, R. P. Golingo, S. L. Jackson, E. A. Crawford, and D. J. Den Hartog. Sheared flow stabilization experiments in the ZaP flow Z pinch. Physics of Plasmas, 10(5):1683–1690, 2003
8. R. P. Golingo, U. Shumlak, and B. A. Nelson. Formation of a sheared flow Z pinch. Physics of Plasmas, 12(6): 062505, 2005
9. U. Shumlak, C. S. Adams, J. M. Blakely, B.-J. Chan, R. P. Golingo, S. D. Knecht, B. A. Nelson, R. J. Oberto, M. R. Sybouts, and G. V. Vogman. Equilibrium, flow shear and stability measurements in the Z-pinch. Nuclear Fusion, 49(7):075039 (9pp), 2009
10. U. Shumlak, J. Chadney, R. P. Golingo, D. J. Den Hartog, M. C. Hughes, S. D. Knecht, W. Lowrie, V. S. Lukin, B. A. Nelson, R. J. Oberto, J. L. Rohrbach, M. P. Ross, and G. V. Vogman. The Sheared-Flow Stabilized Z-Pinch. Fusion Science and Technology, 61(1T):119–124, Jan 2012

Back-up slides

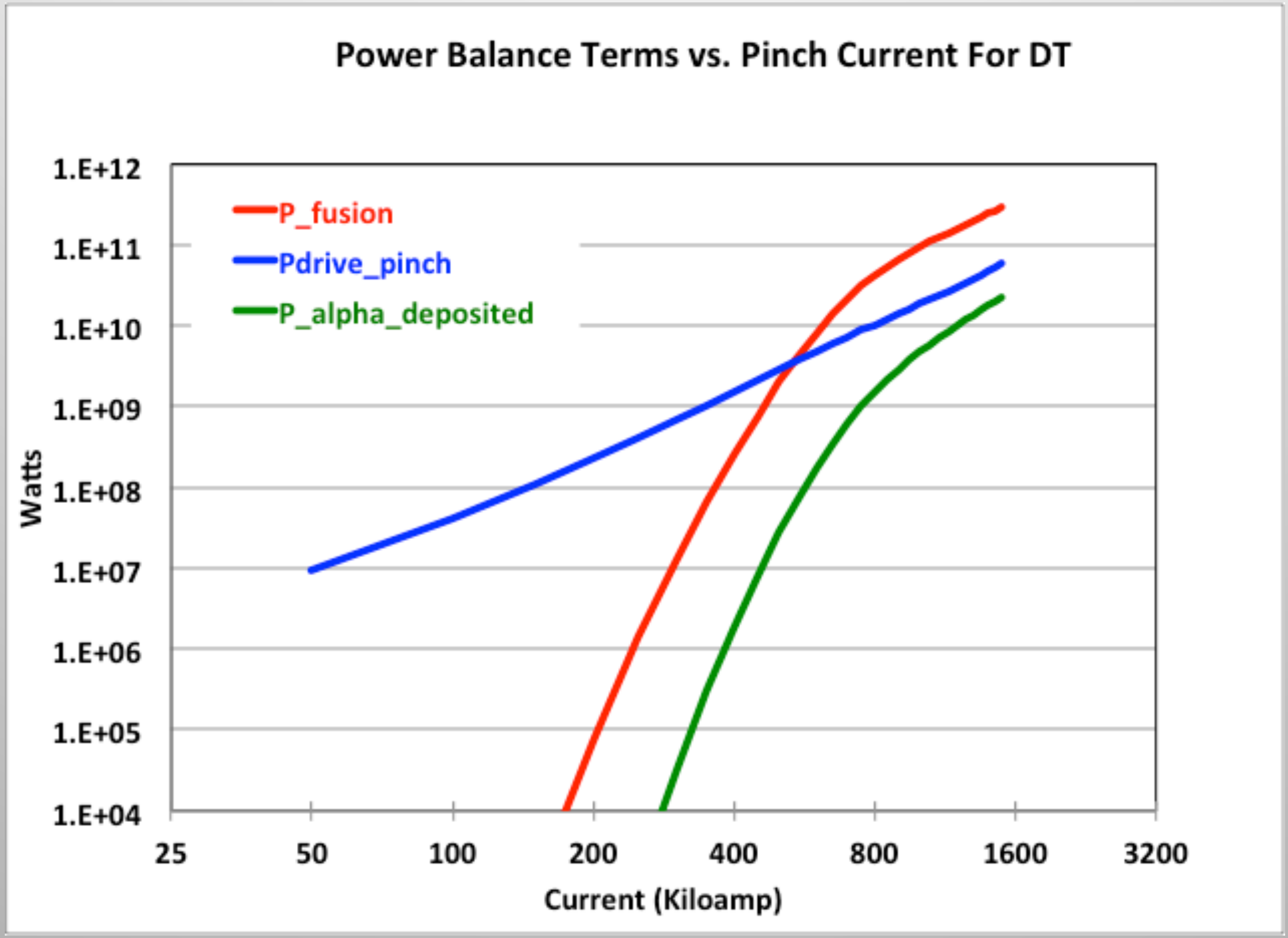
Reactor Development path requires ~30x increase in pinch current from existing capabilities

Development Path Platform -->			ZAP	2xZap	4xZap	FUZE = 6x ZaP	Scientific Breakeven	Engineering Breakeven	Prototype Reactor
Definition	**Symbol**	**Unit**	**Existing Experiment**	**Alpha Mid-term**	**Alpha Mid-term**	**Alpha Goal**	**Pfusion > Pohmic**	**Ufusion > Ugun**	**Ufusion > 5 Ugun**
Plasma									
Current	Ipinch	kA	50	100	200	300	700	1000	1500
Radius	a	mm	10.0	3.94	1.53	0.865	0.241	0.166	0.150
Length	H	m	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Volume	V	cm^3	157080	24340	3669	1176	91	43	35
Density	n	m^-3	3.18E+22	2.05E+23	1.36E+24	4.25E+24	5.48E+25	1.16E+26	1.41E+26
Temperature	T	keV	0.035	0.141	0.564	1.27	6.91	14.1	31.7
Magnetic field	B	Tesla	1.00	5.09	26	70	582	1210	2006
Energy Confinement Time	TauE	usec	2.60	3.10	3.43	3.41	2.55	1.97	1.44
Lawson Parameter	nTauE	sec/m^3	8.29E+16	6.37E+17	4.67E+18	1.45E+19	1.40E+20	2.29E+20	2.04E+20
Peak Power									
Fusion Power (if DT)	Pfusion	GW	0.000	0.000	0.000	0.000	7.35	96.0	349
Ohmic Power	Pohmic	GW	0.035	0.113	0.376	0.782	4.32	6.40	5.20
Power input to electrodes	Pgun	GW	0.101	0.296	0.999	2.18	13.5	29.9	36.9
Pulse Length	T_Pulse	uSec	0.0	32.3	69.9	93.6	145	168	228
Neutron Yield									
Fusion Yield (if DT)	Ydt		4.8E-06	2.9E+03	3.1E+09	1.4E+12	2.4E+16	3.9E+17	6.7E+18
Fusion Yield (if DD)	Ydd		2.2E-09	4.0E+01	8.6E+07	3.3E+10	3.1E+14	4.6E+15	1.1E+17
Energy Per Pulse									
Fusion energy per pulse (if DT)	Ufusion	kJ	0.00	0.000	0.000	0.004	66.8	1108	18887
Energy input to gun electrodes	Ugun	kJ	6.54	16.102	44.955	88.1	441	931	3397
Ohmic dissipation per pulse	Uohmic	kJ	2.27	5.923	16.878	32.5	149	280	605
Fractional Burnup per flow time	Fb	%	0.00%	0.00%	0.00%	0.00%	0.48%	4.39%	10.66%
Reactor Gain Ufus/Ugun	Q_pulse		0.00	0.00	0.00	0.00	0.15	1.19	5.56
Driver									
Current	Igun	kA	100	150	251	353	764	1078	1669
Voltage	Vgun	kV	2.0	3.0	5.0	7.3	19.3	27.7	22.1
Energy	Ugun	kJ	6.5	16.1	45.0	88.1	441.4	930.7	3396.8
Power	Pgun	GW	0.101	0.296	1.00	2.18	13.53	29.85	36.91
Efficiency = Ugun/Ubank	η		0.10	0.10	0.10	0.10	0.10	0.10	0.45
Cap Bank Stored Energy	Ucap	kJ	65	161	450	881	4414	9307	7549
Reactor Gain x Driver Efficiency	ηG		0.00	0.00	0.00	0.00	0.015	0.119	2.50
Rep-Rated Performance									
Physics Platforms-Single Shot	Rep-Rate	Shots/Day	50	50	50	50			
Engineering Test Platforms	Rep-Rate	Hz					1	1	10
Average Input Power	Pgun_avg	MW					0.441	0.931	34
Average Fusion Power	Pfusion_avg	MW					0.067	1.108	189

Prototype reactor:

- Discharge Current / Volts
  = 1.7 MA / 22 kV
- Rep-rate / Pulse Length
  = 10 Hz / 230 uS
- Fusion energy per pulse
  = 19 MJ
- Average Fusion power
  = 190 MJ
- Reactor Q ~ 5

Power Balance projections show reaching 500-700 KA using 50-50 DT achieves "Scientific Breakthrough" as defined by Pfusion > Pinput



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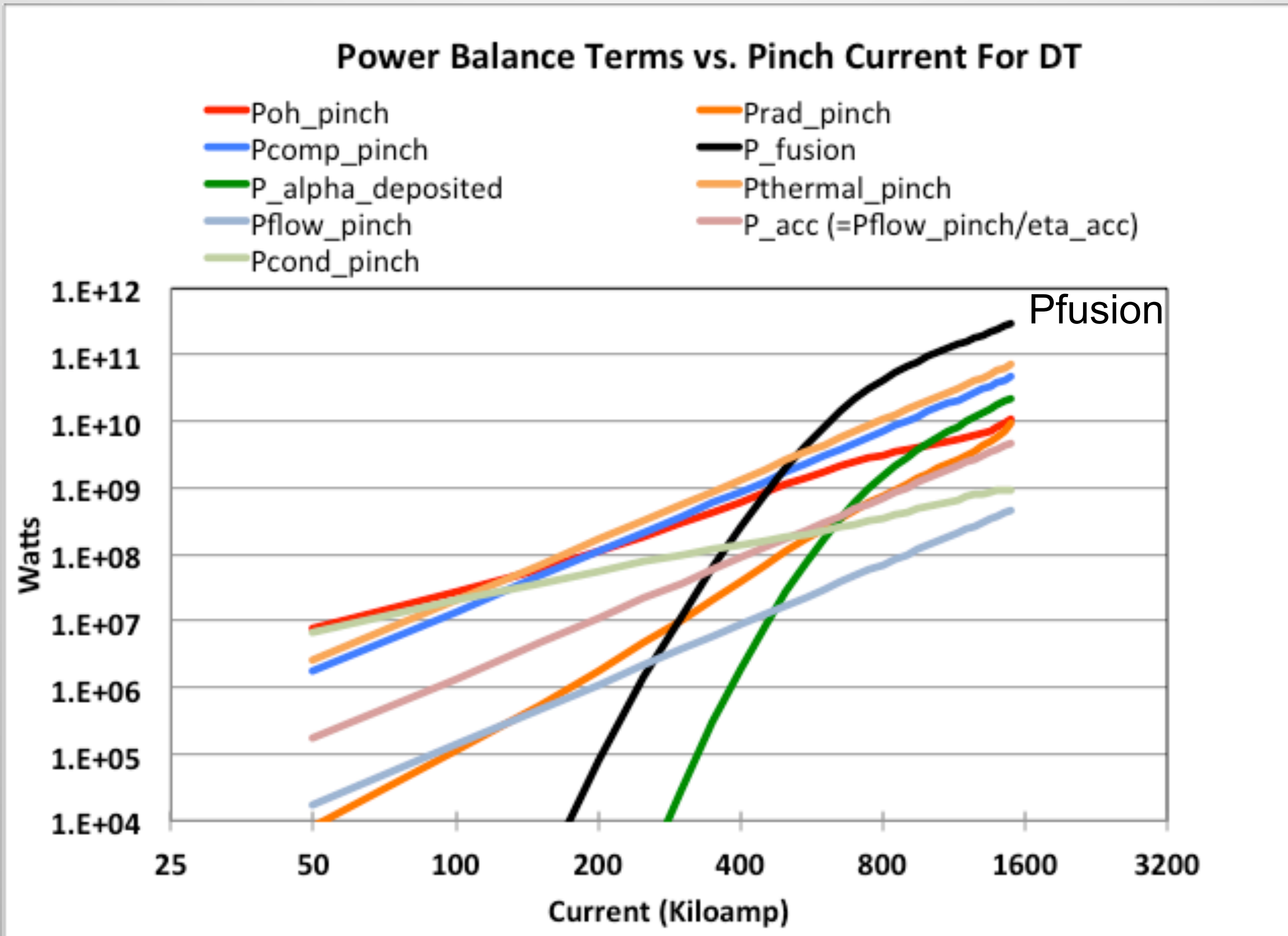
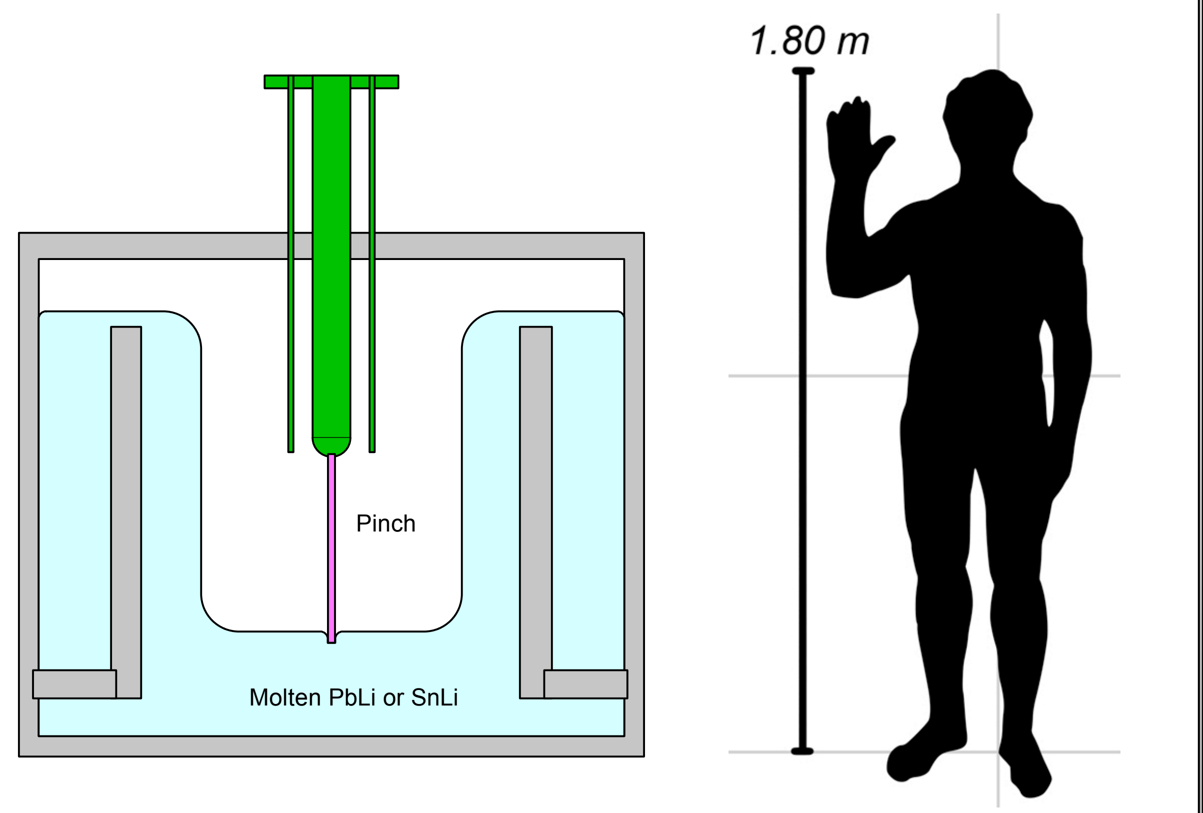


The pinch is short, ~10-50 cm long, so the reactor can be small and modular

5” D-size Ignitron



Heilmeier's Catechism

- What are you trying to do? Articulate your objectives using absolutely no jargon.
  - Scale the ZAP device from 50 kA pinch current to 300 kA pinch current (from ~150 kA discharge current to ~450 kA discharge current) while maintaining stability of the pinch for 10's of microseconds.
  - Scope out a reactor concept that has compelling technology advantages if the system scales to reactor conditions.

Plasma Conditions	Existing (ZAP)	ALPHA (FUZE)	Reactor
Pinch current (kA)	50	300	1500
Total discharge (kA)	150	500	1700
Pinch radius (mm)	10	0.7	0.05
Ion Density (m^{-3})	1E+22	2E+24	3E+26
Temperature (kev)	0.1	4	>25
Magnetic field (tesla)	1	90	6000
Lawson n-tau (m^{-3} sec)	1E+17	1E+19	4E+20

- How is it done today, and what are the limits of current practice?
  - The classic z-pinch, with current flowing axially in a stationary plasma between two electrodes, was the very first concept for confining and heating plasma [W.H. Bennett, Phys.Rev. 45 p890 (1934)].
  - The system suffers severe instabilities- a sharp pinch develops in a single location, which heats a very small volume to fusion conditions, but also terminates the plasma in tens of nanoseconds.
  - Much research in the intervening time has attempted to suppress the instabilities
    - including adding an external magnetic field in the direction of current flow (screw pinch)
    - wrapping the axial system into a toroidal shape and driving current inductively (toroidal pinch, tokamak)
    - adjusting the internal profiles of current, density, and flow velocity (M.G. Haines, Plasma Phys. Control. Fusion 53 (2011) 093001.
  - Plasma flowing in an axial direction with a flow velocity that is sheared in the radial direction has been shown to stabilize a 1 m long x 1 cm diameter 50 kA z-pinch column for 20-40 usec
  - This is an interesting result because it was predicted by most others that velocities near the Alfven speed would be needed to stabilize the pinch. Shumlak's calculation indicated that velocities of about 1/10 the Alfven speed would be enough to stabilize-- and this was born out in his experiments.

Heilmeier's Catechism

- What's new in your approach:
  - We are building unprecedented capability and flexibility into a new device which accommodates the following:
    - Higher input energy, power, and gas loading.
    - A modular (12 independent section) 20 kV capacitor bank to allow a variable and flexible current pulse.
    - Multiple pulsed gas valves (9) to allow a variable and flexible injection of gas
  - We are applying the most recent state-of-the-art computer simulations to resolve the microscopic (kinetic vs fluid) nature of the experiment as well as the fluid nature and whole-device macroscopic behavior.
- Why do you think it will be successful?
  - This type of scale-up has never been attempted before, but the existing experimental results, projected performance based on modest extrapolations, building in experimental flexibility, and application of world-class computer simulations provide a sound foundation for improving the the state of the art and success.
- If you're successful, what difference will it make?
  - Achieving goals of the project, while not approaching the conditions required for a fusion reactor, will nevertheless be suitable for several exciting applications:
    - Intense, neutron source, >1e11 neutrons per pulse
    - Ultra-intense (10 MW) thermal plasma light source operating at a plasma temperature of several kilo-electron volts.
- What are the risks and the payoffs?
  - Discussed briefly in other areas.
- How much will it cost?
  - $5M
- How long will it take?
  - 3 years
- What are the midterm and final "exams" to check for success?
  - Reproduce ZAP results with new hardware in year 1
  - Extend performance factor of 2 in year 2
  - Achieve 6X goal in year 3.

Lawrence Livermore National Laboratory